Guest Editorial
Special Issue on Antenna Array Enabled Space/Air/Ground Communications and Networking

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I. Introduction

WITH the rapid development of electronic and information technologies, the Internet of Everything (IoE) has become one of the trendiest topics in both academia and industry. Therein, many types of space/air/ground platforms need to be connected to networks for breaking down the isolation of information islands and providing various services. Space/air/ground platforms, such as satellites, unmanned aerial vehicles (UAVs), airships, balloons, terrestrial vehicles, and high-speed trains (HSTs) have emerged for accomplishing various complex tasks. Wireless communication is one of the most important technologies to support the real-time delivery of control commands and mission-related data. On the other hand, the space-air-ground integrated network has become a promising paradigm for the six-generation (6G) mobile communication network, where the aerospace and terrestrial vehicles may need to connect to existing mobile cellular networks or act as base stations (BSs) or relays to assist terrestrial wireless communications. To meet the ever-increasing demands of high capacity, wide coverage, low latency, and strong robustness for communications, it is promising to adopt large-scale antenna arrays at the transceivers to obtain considerable array gains and improve the channel quality. Antenna array-enabled beamforming technologies can facilitate spectrum reuse, interference mitigation, coverage enhancement, and physical-layer security. Antenna arrays can also be used to promote the sensing capability of space/air/ground networks, where the sensing information may be carefully processed to assist communications. However, enabling antenna array for space/air/ground communication networks poses specific, distinctive, and tricky challenges in antenna array design, physical layer, multiple access control layer, and network layer. As a result, numerous new research issues require to be addressed, which cover a wide range of disciplines including communication theory, network theory, antenna theory, signal processing, protocol design, resource allocation, optimization, hardware implementation, and experimentation.

This Special Issue aims to focus on the theoretical analysis and practical design for antenna array-enabled space/air/ground communications and networking. Our call for papers received a strong response from the community, and more than 70 papers have been received, many of which were of extremely high quality. However, due to the tight publication schedule of the Special Issue and the limited number of papers that can be accepted, finally, 20 articles have been accepted and will be published. In addition, a survey paper [A1] was written by a team of Guest Editors, which aims to overview the field of antenna array-enabled space/air/ground communications and networking.

The 20 articles included in this issue are in the areas of 1) theoretical analysis of multi-antenna communication; 2) beamforming design for space/air/ground communications; 3) reconfigurable intelligent surface (RIS) enabled space/air/ground communications; and 4) network architecture and protocol design. A brief account of each of these articles is given below.

II. Theoretical Analysis of Multi-Antenna Communications

In [A2], Ding *et al.* adopt a unified spatial bandwidth viewpoint to review the theoretical basis of the achievable spatial degree of freedom (DoF) in line-of-sight (LoS) channels in large-scale antenna array (LSAA)-based communications. An analytical framework based on spatial bandwidth analysis is developed, under which three elementary problems corresponding to three basic orthogonal receiving directions are investigated. For each of them, accurate, simple, and

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interpretable closed-form approximations for the achievable spatial DoF are derived, and the spatial region where a sufficient amount of spatial DoF is expected available is determined.

In [A3], Zheng *et al.* focus on the performance of cell-free massive multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) systems with both fully centralized and local minimum mean square error (MMSE) combining in HST communications. Considering the local maximum ratio (MR) combining the large-scale fading decoding (LSFD) cooperation and the practical effect of Doppler frequency offset (DFO) on system performance, exact closed-form expressions for uplink spectral efficiency expressions are derived. HST communications with small cell and cellular massive MIMO-OFDM systems are compared in terms of spectral efficiency. The train antenna-centric cell-free massive MIMO-OFDM system is designed for practical implementation in HST communications.

In [A4], Yan *et al.* propose an energy-efficient dynamic-subarray with fixed true-time-delay (DS-FTTD) architecture to solve the beam squint problem for Terahertz (THz) wideband hybrid beamforming. A low-complexity row-decomposition (RD) algorithm is developed to design hybrid beamforming matrices for the proposed DS-FTTD architecture. The extensive simulation results show that the DS-FTTD architecture with the RD algorithm achieves near-optimal array gain and significantly higher energy efficiency than the existing architectures, and is robust when the channel state information (CSI) is imperfect with errors.

In [A5], Alshawaqfeh *et al.* aim to develop a reduced complexity detector for signed quadrature spatial modulation (sQSM) schemes. Toward this end, a tree search optimal low complexity detector for the sQSM MIMO system is proposed and analyzed. The proposed detector expands the computationally complex maximum likelihood (ML) detector for sQSM into a tree-structure representation, which can expeditiously find the branch corresponding to the minimum error without tracing the entire nodes as in the ML case. It is reported that the proposed algorithm achieves the exact error performance as an ML detector but with a substantial reduction in computational complexity.

In [A6], Shen *et al.* investigate the application of orthogonal time-frequency space (OTFS) for the grant-free random access with massive MIMO in low-Earth-orbit (LEO) satellite communications. The input-output relationship in the single-input single-output (SISO)-OTFS system is first analyzed and then extend to the random access with massive MIMO-OTFS. Next, by exploring the two-dimensional burst block sparsity in the delay-Doppler angle domain, a 2-D pattern coupled hierarchical prior with the sparse Bayesian learning and covariance-free method (TDSBL-FM) is developed for the channel estimation and active device detection.

III. Beamforming Design for Space/Air/Ground Communications

In [A7], Wang *et al.* propose a joint hybrid precoding/combining scheme based on the concept of the equivalent channel and the singular value decomposition (SVD) technique for both single-user and multi-user millimeter wave (mmWave) massive MIMO systems. The angle information used to construct the analog precoder and combiner is obtained via a two-stage method with the assistance of the optimal unconstrained precoder and the defined intermediate channel. Then the concept of equivalent channel is adopted to obtain the digital precoder and combiner. The results show that the proposed schemes can achieve superior performance with lower complexity compared to the existing ones.

In [A8], Gao *et al.* propose a deep learning (DL)-based end-to-end (E2E) approach for aerial multi-user broadband hybrid beamforming. By modeling the key transmission modules as an E2E neural network, the proposed approach provides a unified hybrid beamforming framework for both time division duplex (TDD) and frequency division duplex (FDD) aerial massive MIMO and OFDM systems with implicit CSI. Different from conventional approaches separately processing different modules, the proposed solution simultaneously optimizes all modules with the sum rate as the optimization object. The numerical results show that the proposed DL-based scheme can achieve significantly better performance than traditional schemes.

In [A9], Yuan *et al.* consider a UAV-enabled multi-user network with nonlinear wireless power transfer (WPT). Acting as an energy source, the UAV installs an antenna array and transfers energy to the multiple sensor nodes (SNs) via wireless signals. The UAV energy efficiency particularly for the WPT task is characterized, and an efficiency maximization problem is subsequently formulated in which the analog beamforming and UAV trajectory planning are jointly determined. To deal with the nonconvex joint optimization problem, a cosine-based approximation for the 3-D antenna pattern and an iterative algorithm are proposed.

In [A10], Yu *et al.* study the joint design of power allocation, beamforming, and positioning for UAV-aided mmWave systems, with the objective of maximizing the energy efficiency, under the constraints of maximum transmitting power, minimum data rate from the ground users and positioning range of the UAV. To address the above problem, the positioning of the UAV is first obtained, with the help of an approximate beam pattern. Then, near-optimal beamforming and closed-form power allocation are derived given the obtained position, with the help of the block coordinate descent method. The simulation results verify the effectiveness of the developed joint schemes and show superior performance.

In [A11], Bai *et al.* develop a UAV-enabled multi-user secure backscatter communications (BackComm) system using analog beamforming and randomized continuous wave (RCW) techniques, where the multiple users are supported by the multi-carrier RCW over a single low-complexity radio frequency (RF) chain. The closed-form of the secrecy rate is studied with the approximations, which is then maximized by jointly optimizing the beamforming together with the UAV's location and the RCW settings. The simulation results show that the secrecy rate can be significantly improved compared with the benchmark schemes.

In [A12], Du *et al.* investigate a jammer-aided UAV covert communication system. By considering the general composite fading and shadowing channel models, the exact probability density (PDF) and cumulative distribution functions (CDF) of the signal-to-interference-plus-noise ratio (SINR) are derived. Important covert performance metrics including detection error probability and covert rate are derived. With the help of the obtained performance metrics, the covert rate maximization problem is formulated as a Nash bargaining game, and the Nash bargaining solution is introduced to investigate the negotiation among users.

In [A13], Liu *et al.* study the optimization of beamforming for mmWave dual-functional radar communication (DFRC) vehicle-to-everything (V2X) system where a vehicle tries to communicate with a front vehicle or a gNodeB while performing radar sensing at the same time. A novel single-target-multi-beams (STMB) radar beam alignment scheme is proposed, and the hybrid analog-digital beamforming under the STMB scheme is formulated and optimized by maximizing transmission rate subject to radar signal-to-interference-and-noise (SINR) constraints. The numerical results verify the effectiveness and reliability of the STMB scheme and show that the proposed beamformer outperforms the benchmark in both spectral efficiency and minimum radar SINR.

In [A14], You *et al.* investigate the application of integrated sensing and communications (ISAC) in massive MIMO LEO satellite systems. The statistical wave propagation properties by considering beam squint effects are characterized, based on which a beam squint-aware hybrid precoding scheme exploiting statistical CSI is proposed. The simulation results demonstrate that the proposed scheme can operate both the wireless communications and the target sensing simultaneously with satisfactory performance, and the beam-squint effects can be efficiently mitigated in typical LEO satellite systems.

IV. RIS Enabled Space/Air/Ground Communications

In [A15], Zhi *et al.* provide a theoretical framework for understanding the performance of RIS-aided massive MIMO with zero-forcing (ZF) detectors under imperfect CSI. Theoretical expressions for the ergodic rate is derived, based on which two low-complexity majorization-minimization (MM) algorithms are proposed to respectively optimize the sum user rate and the minimum user rate. The analytical results reveal several meaningful rate scaling orders, which are validated by the simulation results. It is proved that RIS-aided massive MIMO systems with ZF detectors are promising for many applications.

In [A16], Ma *et al.* propose a one-cylinder-based three-dimensional (3D) MIMO geometrical channel model for aerial intelligent reflecting surface (AIRS)-aided MIMO communications. To create smart radio environments, several novel methods of optimizing the phase shifts at the IRS elements are proposed. Then, channel statistical properties of the proposed channel model, including channel impulse response (CIR), spreading function, space-time correlation function, and channel capacity are thoroughly derived and simulated. It is found that multipath and Doppler effects in radio propagation environments can be effectively mitigated via adjusting the phase shifts of IRS.

In [A17], Zhao *et al.* conceive an air-to-ground communication paradigm where a UAV-mounted BS equipped with multiple antennas sends information to multiple ground users (GUs) with the aid of a simultaneously transmitting and reflecting RIS (STAR-RIS). A sum-rate maximization problem is formulated for the joint optimization of the UAV's trajectory, the active beamforming at the UAV, and the passive transmission/reflection beamforming at the STAR-RIS. An online decision-making framework is developed, employing reinforcement learning (RL) to simultaneously adjust both the UAV's trajectory as well as the active and passive beamformer.

In [A18], Zheng *et al.* consider a RIS-aided LEO satellite communication system, which copes with the time-varying channel between the high-mobility satellite (SAT) and a ground node (GN) cost-effectively. A new architecture where RISs are deployed at both sides of the SAT and GN is proposed. The cooperative passive beamforming (CPB) design over LoS-dominant single-reflection and double-reflection channels is studied. The simulation results demonstrate the substantial performance gains achieved by the proposed system architecture under the proposed beamforming design and transmission protocol, as compared to various baseline schemes such as the conventional reflect-array and one-sided RIS.

In [A19], Deng *et al.* consider a reconfigurable holographic surface (RHS) integrated with a user terminal to support LEO satellite communications. To obtain the desired beam directions toward the satellites, an LEO satellite tracking scheme based on the temporal variation law is proposed such that frequent satellite positioning can be avoided. A holographic beamforming algorithm for sum rate maximization is then developed where a closed-form for the optimal holographic beamformer is derived. The simulation results show that the RHS provides a more cost-effective solution for pursuing a high data rate compared with the phased array.

In [A20], Chen *et al.* consider the use of an active reconfigurable intelligent omni-surface (RIOS) to a vehicular communication system for mitigating double fading effect. Specifically, the active RIOS is mounted on the vehicle window to enhance transmission for users in the vehicle and for adjacent vehicles. The transmit precoding matrix at the BS and RIOS coefficient matrices are jointly optimized to minimize the BS's transmit power relying exclusively upon the imperfect knowledge of the large-scale CSI. The simulation results validate the significant potential of the active RIOS to vehicular communications in terms of double fading mitigation and transmit power savings as compared to conventional RIS, and reveal robustness against mobility-induced CSI imperfection.

V. Network Architecture and Protocol Design

In [A21], Liu *et al.* propose a blockchain-based credential management scheme in space-air-ground integrated vehicular networks (SAGVN), which enables secure and distributed setup of system public parameters and collaborative credential issuance for anonymous authentications in SAGVN. On addressing the on-chain efficiency issue, the proposed scheme designs an on/off-chain communication protocol with succinct commitments and zero-knowledge proofs for veritable operations of participants in SAGVN. A real-world blockchain network is set up and extensive experiments are conducted to show the feasibility and efficiency of the scheme.

VI. Acknowledgment

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Appendix: Related Articles

[A1] Z. Xiao *et al.*, "Antenna array enabled space/air/ground communications and networking for 6G," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196320.

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[A5] M. Alshawaqfeh, A. Gharaibeh, and R. Mesleh, "Optimal low complexity detector for signed-quadrature spatial modulation MIMO system," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196107.

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[A12] H. Du, D. Niyato, Y. Xie, Y. Cheng, J. Kang, and D. I. Kim, "Performance analysis and optimization for jammer-aided multi-antenna UAV covert communication," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196131.

[A13] B. Liu, J. Liu, and N. Kato, "Optimal beamformer design for millimeter wave dual-functional radar-communication based V2X systems," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196089.

[A14] L. You *et al.*, "Beam squint-aware integrated sensing and communications for hybrid massive MIMO LEO satellite systems," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196114.

[A15] K. Zhi, C. Pan, G. Zhou, H. Ren, M. Elkashlan, and R. Schober, "Is RIS-aided massive MIMO promising with ZF detectors and imperfect CSI?" *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196097.

[A16] Z. Ma *et al.*, "Modeling and analysis of MIMO multipath channels with aerial intelligent reflecting surface," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196112.

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[A21] D. Liu, H. Wu, C. Huang, J. Ni, and X. Shen, "Blockchain-based credential management for anonymous authentication in SAGVN," *IEEE J. Sel. Areas Commun.*, early access, 2022, doi: 10.1109.JSAC.2022.3196091.

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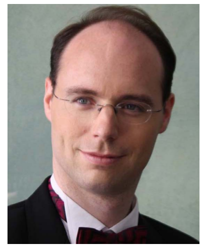

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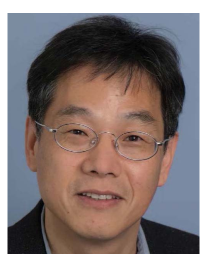

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